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COMPUTATIONAL EFFICIENCY IN THE AMIS NAVAL OFFICER ROTATION MOD--ETC(U)
1979 S J SIVERD , G L THOMPSON N00014-75-C-0621
UNCLASSIFIED MSRR-442 NL

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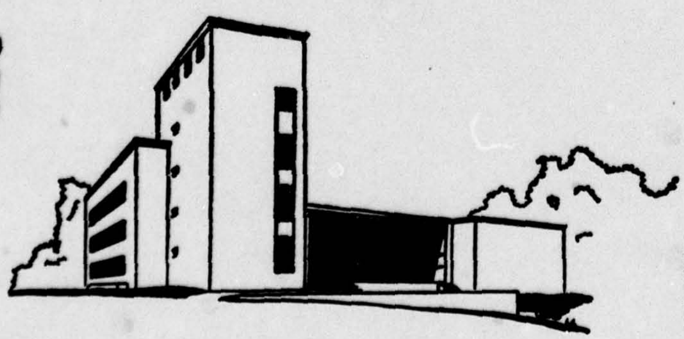

W.P. 23-79-80

Management Science Research Report No. 442

Computational Efficiency in the AMIS Naval Officer Rotation Model

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This report was prepared as part of the activities of the Management Sciences Research Group of Carnegie-Mellon University under contract N00014-75-C-0621 NR 047-048 with the Office of Naval Research (ONR) and contract N00014-76-C-0932 with ONR and the US Navy Bureau of Personnel.

Abstract

Recent changes in a large scale macro planning model used to determine a "best fit" of Naval Officers and billets are discussed. Problem reformulation from a linear program to a sparse transportation model is followed and the implementation of an advanced start procedure to achieve solution continuity is also presented. Suggestions are made for further research that would enhance the applicability of the model.

This report is a summary of the work done to date on the Automated Management Information System (AMIS) which is a macro planning model used by the Bureau of Naval Personnel to provide guidance for Naval Officer assignments. The material discussed below builds upon the research summarized by Cass, Charnes, Cooper and Niehaus in [1] and Thompson and Eubanks in [9]. Section A discusses the problem conception and background. Section B presents a linear programming formulation of the problem that evolved into the transportation model formulation discussed in Section C. Section D then suggests some areas for further work on this project.

Section A. Problem Conception and Background

The officer rotation problem of the US Navy is one of a class of personnel problems that is frequently encountered in manpower planning. The problem is to determine a "best fit" of the jobs in the organization and the individuals in the personnel inventory. This "fit" is a measure of the match (or mismatch) of the attributes desired in the various jobs and the attributes possessed by the various personnel categories. While many organizations may be concerned with attaining this fit subject only to budget constraints, the Navy has other objectives that confound the problem. In addition to attempting to maximize the

present organizational effectiveness by finding the best match of individuals and jobs, the career development of the officers involved must also be considered. It is in the Navy's interest to develop officers familiar with several functional areas, in addition to cultivating both sea and shore experience. Thus the officers are rotated among the available jobs every two or three years and the goal of attaining a current best fit must be tempered by the desire to give each officer assignments to a variety of different jobs.

The problem described in this paper is not the classical 0 - 1 assignment problem, where specific individuals are assigned to specific jobs. Instead the personnel inventory and positions to be filled are grouped into attribute categories and the desired assignments are of the form "assign x individuals from category A to positions of category B ". This type of assignment guidance is desirable for planning purposes, as the actual detailed assignment of specific individuals is handled manually by assignment personnel who consider the multitude of unique factors related to the specific individuals and the specific billets to be filled. The solutions to this problem are used not only for planning guidance in the actual assignment of officers, but can also be used to examine different alternatives for the assignment of various groups of officers.

The officer categories in this problem are characterized by grade and designator, and the job categories, called "billets" in Navy jargon, are characterized by grade, designator and priority.

Ten grades are considered, from Ensign through Captain. The designators are codes that reflect the fields of expertise and degree of competence of both the officers holding these designators and the billets to be filled. Priorities are associated only with billets and reflect the relative importance of the various billets.[1]

According to [1], manual decisions by a committee of assignment personnel were first used for planning guidance beginning in about 1966. The objective of the committee was to determine the number and category of officers to be be distributed to each billet category. In addition to attempting to maximize the overall quality of fit of the entire officer corps, the committee was also charged with observing certain policy factors, some of which are shown in figure 1.

This figure adopts the terminology of both [1] and [9]. The phrase "up-detailing" is used for instances where an officer is assigned to a billet that would ideally be filled by an officer of a higher grade. Likewise "down detailing" refers to instances where an officer is assigned to a billet that would ideally be filled by someone with a lower grade than he possesses. "Cross-detailing" refers to instances where an officer is assigned to a billet that calls for a designator different than the designator of the assigned officer.

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[1] For a detailed definition of the four billet priorities see [9].

1. Up detailing is preferable to down detailing.
2. If an officer is up detailed, send him to a lower priority job.
3. If and officer is down detailed, send him to a higher priority job.
4. If an officer is cross-detailed, send him to a lower priority job.
5. Do not up or down detail more than one grade (with a few exceptions).

from Thompson and Eubanks, ref. [9]

Figure 1. Policy Rules used in Assignments.

Obviously this is a complex problem to solve manually, especially in view of the fact that the committee had to consider between 45,000 and 50,000 officers and a similar number of billets. Both the size and the complexity of the problem led to the desire for automated assistance. Cass, Charnes, Cooper and Niehaus discussed the feasibility of automating this problem in [1] in 1973 and the following section presents the formulation that grew out of their work.

Section B. Linear Programming Formulation

The officer rotation model was first formulated and solved as a linear program. During this time period it became known as AMIS, an acronym that stands for Automated Management Information System. The model was based on the assumption that the best fit of the personnel inventory and billets could be attained by

maximizing the summation of the individual officer-billet utility values over all the officer and all the billet categories.

The utility values were generated in a manner that reflected the policy factors of figure 1. An "up and down detailing" matrix was used to specify the value of assigning officers of various grades to billets of various grades. Likewise a "cross detailing" matrix was devised to specify the value of assigning officers of the various designators to billets calling for specific designators. This scoring system is described in detail in [9]. The priorities of the billets were also considered, and the utility values were adjusted up or down to attempt to conform to the policy factors.

As the linear programming (LP) formulation requires one constraint for each inventory category and one for each billet category, the potential existed to generate extremely large problems. For example with 10 grades, 76 designators and 4 billet priorities, an LP with two million variables and 3800 constraints could have resulted.[1] To avoid generating such large

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[1] Requiring a variable for each potential pair of inventory and billet categories would yield:

number of potential billet categories:
10 grades x 76 designators x 4 priorities = 3040

number of potential inventory categories:
10 grades x 76 designators = 760

3040 x 760 = 2,310,400

problems, two conventions were adopted. First, a threshold value for minimum utility scores was set. If the total value of the utility score for both up/down detailing and cross detailing did not meet this threshold, then the variable representing this specific assignment was dropped from the problem. The second method of decreasing the problem size was to use dynamic dimensions when formulating the problem. Rather that use fixed size arrays that would handle any similar problem that might arise, the code was written to generate a problem that included only the variables which represented nonempty inventory and billet categories.[1]

These two techniques reduced the LP formulation to a manageable size, resulting in problems with approximately 16,000 variables and 1400 constraints.[2] These problems were solved with IBM's linear programming code MPS in about 25 - 30 minutes of CPU time, as reported in [9]. The LP formulation was successfully implemented and was used until 1978 when the transportation formulation discussed in the next section was implemented. Figure 2 lists the primary benefits of the LP solutions to the AMIS problem.

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[1] As this problem is usually ran quarterly and personnel availabilities and billet requirements do change, different categories may be empty on each run.

[2] Note that even with this reduction in problem size, the LP tableau was still quite sparse, with densities as small as .2% not uncommon.

> They present an achievable plan that optimizes the use of the available officer inventory.
>
> They show where officer excesses exist, and how they should be used. They also show where officer deficiencies exist, and suggest assignments to compensate for these.
>
> They give a numerically feasible plan for apportioning officers to multi-designator billets.
>
> They provide assignment personnel with useful information for short-term planning.
>
> They help answer questions such as: "Why didn't I get the grade of officer I asked for in this position?", "Why can't officer X get the billet he asked for ?", "Why is Captain Z assigned to a Commander's billet?"
>
> from Thompson and Eubanks, ref. [9]

Figure 2. Uses of AMIS LP Solutions.

In the two previous reports on this project, [1] and [9], ideas were presented for the extension and further development of techniques to solve the AMIS problem. These recommendations are summarized in figure 3.

1. Develop suitable data files for automated use.

2. Develop an information system for use by the assignment personnel that allows on-line examination of the billet and officer files.

3. Replace the LP formulation with a fast transportation code.

4. Develop conversational models for the simultaneous consideration of multiple officer-billet combinations.

5. Take account of other attributes in computing utility scores.

6. Consider other objectives such as minimize travel costs (or distances) and maximize officer preferences.

7. Consider multiple period formulations, i.e. plan not only the next assignment, but also the one to follow.

Figure 3. Previous Recommendations for changes to AMIS.

Suitable automated files for the officer and billet categories have been developed (recommendation 1). In addition, individual officer records are now available on-line to the assignment personnel (part of recommendation 2). The following section of this paper will discuss recommendation 3, replacing the LP with a fast transportation code. Points 4, 5 and 6 have been included in the development of a conversational model that considers multiple officer-billet combinations, discussed in [5] and [9]. This conversational model allows a weighting of the qualification match and the distances between the officers current locations and their new assignments. [6] also discusses the feasibility of including the additional attributes of time-in-grade and career field preferences in the AMIS program.

Section C. Transportation Model Formulation

As mentioned in section B, the LP formulation of the AMIS program took about 25 to 30 minutes of CPU time to execute. The program was ran quarterly for planning guidance and the advantage of also using AMIS to examine the impact of changes in policy, inventory or requirements became apparent. With the potential of more frequent runs, the need to decrease the execution time arose. Thus, alternative formulations for the problem were explored.

The AMIS problem is easily formulated as a transportation problem. The classical transportation problem, discussed in [2], [10] and most other operations research texts, is concerned with minimizing the transportation cost of shipping commodities from multiple source points to multiple demand points. If the source points are viewed as the personnel categories and the demand points are viewed as the billet requirements, then the similarity between AMIS and the transportation problem is obvious. To maintain the line of development of the LP formulation, the transportation problem was set up to maximize overall utility, rather than the more commonly encountered objective of minimizing cost.[1]

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[1] It should be noted that a potential disadvantage of modeling the AMIS problem as a transportation problem, instead of an LP, is that only certain types of additional linear constraints on the variables can be included in a transportation problem. No constraints other than meeting demand and not exceeding inventory availabilities have been incorporated in AMIS so far, thus the transportation model has sufficed for this implementation.

The first transportation formulation was called SPADIS, as it capitalized on the sparseness of the transportation tableau and utilized the distance function (SPArse, DIStance) in determining the cycle crated by the in-coming cell [8]. This code created a dynamically dimensioned problem, as did the LP formulation. Thus, any shift in the number of nonempty inventory or billet categories resulted in a change in the size of the problem. The problems generally consisted of about 300 rows and slightly under 1000 columns. The threshold value technique of limiting the number of permissible officer-billet combinations used in the LP formulation was continued and the resultant transportation tableaus were about 4 to 5% dense.

Initially some problems were encountered in obtaining feasible solutions. This was because certain inventory designators were so restricted by the cross detailing matrix that few possible assignments for these specific designators would meet the minimum threshold value, initially set at 1000 points. When the threshold was dropped to 800 points for these designators, feasible answers were obtained after approximately 4300 pivots and three minutes of CPU time on a DEC 2050 processor.[1] However, examination of these solutions revealed some undesirable assignments. Dropping the threshold value to 800 on the troublesome designators allowed some officers to qualify for an assignment based solely on their grade match with the billet

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[1] This time was with the TOPS operating system and included input and output from disk files.

grade requirement, regardless of the degree of their designator mismatch. Thus, cases of large imbalances between the inventory and billets resulted in officers of the desired rank ending up in assignments for which they had no training. To avoid this, the assignment of officers to "slack" assignments or the filling of billets with "slack" officers was permitted. These assignments actually reflect officers that were not assigned and/or billets that were not filled. After this change, and returning the threshold value to 1000 as before, the solutions yielded acceptable assignments.[1]

The dual degeneracy of the transportation (and LP) solutions was surprising. Due to the limited number of different utility scores used in the up/down detailing and the cross detailing matrices, many alternate optima exist. In fact, there are approximately 200 nonbasic feasible cells with zero reduced costs at the optimum of a typical solution. Recognizing that making just one of these degenerate pivots could yield as many as 200 potentially different adjacent alternate optima, the total number of alternate optima is an astronomical figure.

The existence of the multiple solutions caused another problem, one that was understandable from a theoretical prospect,

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[1] Note that even though the number of inventory and billet categories had increased during this time frame, resulting in problems in the range of 320 x 1040 with a density of about 4%, the "better" distribution of the density permitted solutions in about 1100 pivots, instead of the approximately 4300 pivots when the slack column (or row) was restricted.

but disturbing from the user's viewpoint. Slight shifts in the data for the problem often yielded what appeared to be major changes in the assignments in the solution. What was actually happening is illustrated in figure 4.

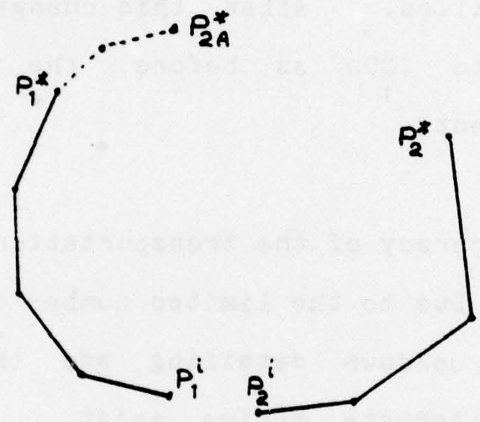

Figure 4. Illustration of different sequences of extreme points with small data shifts.

Consider two hypothetical problems, P_1 and P_2. Let P^i_1 and P^i_2 designate the starting solutions to problems P_1 and P_2, and likewise let P^*_1 and P^*_2 be the respective optima found when the solution technique started from the given starting points. Due solely to the method of choosing the incoming cells during the solution of the transportation problem, the sequences of extreme points resulting from the two starting points may diverge in the solution space, even though the starting solutions P^i_1 and P^i_2 differ only slightly. Thus, given that each sequence

terminates on the first optimum point it reaches, P^*_1 and P^*_2 may be quite different. However, given that these problems are highly degenerate, there may exist (probably exists) some point, call it P^*_{2A}, that is also optimum for problem P_2 and is much closer to P^*_1 than P^*_2 is. Point P^*_{2A} would be more acceptable to managers who were accustomed to seeing solutions in the P^*_1 area. Thus the difficulty could be resolved by finding an alternate optimum to problem P_2 that was nearer to P^*_1. An advanced start procedure was implemented to do this. This procedure is given the "old" optimal point from a preceding solution, i.e. P^*_1 in figure 4, as a starting solution. Then the algorithm moves to an optimum for the new problem which is closer to the old solution, i.e. P^*_{2A} instead of P^*_2.

Several changes were required in the solution techniques to implement this advanced start. First of all, the dynamic problem size had to be eliminated. In order to assure that the cells included in the basis of the preceding solution yield a tree that spans the new problem, the problems must be of the same size. Thus the maximum sizes were determined for the AMIS problem. Examining the inventory revealed that 49 designators had positive entries only for commissioned officer grades and 30 designators had positive entries only for warrant officer grades. Similarly, the billet file showed 61 designators with only commissioned requirements and 31 with only warrant requirements. The calculations of figure 5 yield the maximum dimensions of the AMIS problem, barring any increases in the number of inventory or billet categories. Once these maximum sizes were determined, all

rows (inventory):

49 designators x 6 commissioned grades		=	294
30 designators x 4 warrant grades		=	120
slack row			1
			415

columns (billets):

61 designators x 6 commissioned grades	x 4 priorities	=	1464
31 designators x 4 warrant grades	x 4 priorities	=	496
slack column			1
			1961

Figure 5. Maximum dimensions for the AMIS problem.

problems were generated to have these same dimensions.

As the problems were now about 2.5 times larger than before, 415 x 1961 versus approximately 320 x 1040, the time to generate the utility values became significant. The values used in the up and down detailing matrix and the cross detailing matrix were seldom changed, so rather than generating the utility values for each run, as was done with the LP formulation and SPADIS, they were generated once and stored in a file. This step alone consumed approximately 6 minutes and 30 seconds of CPU time, as it was necessary to generate approximately 32,000 values.[1]

The technique used to currently solve the AMIS problem from the advance start is the rim operator theory of Srinivasan and Thompson, originally presented in [7]. This technique, combined with the features of capitalizing on the sparseness and utilizing the distance function in SPADIS, has been named SPADAD (SPArse,

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[1] All the processing times mentioned in the remainder of this paper are for a DEC 2050 with TOPS operating system.

Distance, ADvanced start).

A theoretically interesting problem that arose in this implementation was the phenomenon of cycling. Although the theoretical possibility of cycling has long been known to exist in linear programs, including transportation problems, few instances of cycling have occurred in practice. In using the rim operator concept in an earlier version of SPADAD, cycling did occur. This was primarily due to the highly degenerate nature of the problem. When changing the flow on the cycle created by forcing a new cell into the basis, frequently the flow on several "giver" arcs was driven to zero simultaneously.[1] If any consistent decision rule was used to choose among the zero flow arcs to determine the exiting cell, then occasionally this cell would reenter the basis later at zero flow and the code would cycle, as the same cell would then again be chosen to exit the basis. This problem was avoided by using a random number generator to choose which cell should leave the basis when the flow on two or more arcs simultaneously reached zero. This random choice prevented any further cycling.

Figure 6 lists some of the various problems used to test SPADAD. The inventory and billets were varied by the factors shown in columns 2 and 4 and the solution times in column 6 resulted. Note that many of the changes were simply to check that

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[1] See [7] for the background on "giver" and "getter" cells in rim operator theory.

	inventory amount	inventory change	billets amount	billets change	no. of pivots	CPU time* (min:sec)
A	0	0	0	0	-	0:46 (overhead)
B	.10	R	0	0	57	0:52
C	.50	.5x	0	0	989	6:00
D	1.00	2x	0	0	3696	8:07
E	0	0	.05	R	98	1:03
F	0	0	.05	2x	376	2:26
G	0	0	.05	.5x	1756	5:58
H	.10	R	.05	R	221	1:31
I	SPADIS from scratch					1:18

R = random change of ± 50
* includes I/O from disk

Figure 6. Changes in data and SPADAD solution times.

the code functioned properly. For example, cases C and D are equivalent to reducing the entire Naval Officer corps by 25% and increasing it by 100%, obviously not realistic cases. The only other case that took a large amount of time to solve was case G, where .05 of the billets were reduced by 50%. This resulted in a large surplus of personnel, and the technique spent a considerable amount of time trying to find out where to place these excess individuals. In cases such as these three, it is better to use SPADIS and solve the problem from scratch than to use SPADAD with the advanced start procedure. SPADAD was designed to produce continuity in solutions to problems in which the rim changes are relatively small. Such continuities cannot be expected to exist when major rim changes are made.

Few instances occur where only the inventory or only the billets change, instead both can be expected to vary slightly in realistic situations. Thus, case H is probably the most

realistic, and its execution time is only 13 seconds longer than solving the problem with SPADIS. SPADAD has met the goals originally set in its implementation: determining optimal solutions that are "close" to the advanced start in a reasonable amount of time. Although there were some problems in its initial implementation, particularly in changing from the DEC 2050 used by us for development to the IBM 370 used by the Navy, SPADAD is currently being used by the Navy to solve the AMIS problem.

Section D. Future Work

This paper has summarized the work on the Navy AMIS project to date. Listed next are five possibilities for further extensions, discussed in increasing order of modeling complexity.

1. Analyzing Scoring Routines

As mentioned in [9], any scoring scheme may lead to paradoxical results. This is especially true of additive scoring schemes such as the one used in AMIS. The various scores assigned by the up/down and cross detailing matrices need to be reevaluated, not only in the context as used within these matrices, but also in the context of their influence on the total score resulting from comparisons between the matrices. Questions such as "does down detailing a Captain to a Commander's job in designator 1310 (yielding a score of 1700) really mean more effectiveness than assigning him to a Captain's job in designator 1321 (which yields a score of 1600)" need to be asked and

answered.

2. Other Attributes

Also the impact on the effectiveness of a particular officer-billet match of considering other attributes in the assignments needs to be evaluated. Some techniques of considering time-in-grade and career preferences in AMIS have been presented in [6]. Also scoring schemes and solution techniques that can consider the additional skill designators, which identify training and experience on a finer grid, should be examined. Whether or not these considerations are worth the additional effort of including them needs to be decided.

3. Priorities

The problem of how to adequately model the various priorities of billets is encountered in AMIS and other manpower models. AMIS artificially reduces the number of billets to be filled to assure adequate personnel are available to attain the desired fill ratios for each billet priority. Other models [3], [4] have used successive solutions to meet this goal - solving the model first with all high priority billets, then again with a lower priority and so on until obtaining a final solution. Different weighting schemes could also be tried to attempt to attain these goals. These techniques, and others not yet conceived, should be examined to determine a better method of enforcing billet priorities.

4. Multiple Period Models

The extension of AMIS to permit the planning of personnel assignments over multiple time periods was initially recommended by Cass et al in 1973 [1]. Although it is difficult to obtain the scores needed to evaluate different sequences of billets for an officer's development, the impact on his career is obvious. More work needs to be done in an attempt to capture this career progression and its long term impact on the effectiveness on the Navy.

5. Other Objective Functions

In addition to the areas of research discussed above, the inclusion in AMIS of the ideas that are developed in the BUPERS conversational program should be considered. These ideas include the consideration of the tradeoffs of various different objectives, such as minimizing travel costs and maximizing the quality of the overall officer-billet matches.

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report 442	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 COMPUTATIONAL EFFICIENCY IN THE AMIS-NAVAL OFFICER ROTATION MODEL.		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER MSRR 442
7. AUTHOR(s) 10 Samuel J. Siverd Gerald L. Thompson		8. CONTRACT OR GRANT NUMBER(s) 15 NØØ014-75-C-Ø621, NØØ014-76-C-Ø932
9. PERFORMING ORGANIZATION NAME AND ADDRESS Graduate School of Industrial Administration Carnegie-Mellon University Pittsburgh, Pennsylvania 15213		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NR 047-048
11. CONTROLLING OFFICE NAME AND ADDRESS Personnel and Training Research Programs Office of Naval Research (Code 434) Arlington, Virginia 22217		12. REPORT DATE
		13. NUMBER OF PAGES 20
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) 12 24		15. SECURITY CLASS. (of this report)
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited. 11 1979

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

14 MSRR-442, WP-23-79-8Ø

18. SUPPLEMENTARY NOTES

9 Management sciences research rept.,

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Manpower Planning, Transportation Model, Assignment Model, Cost/RM Operators.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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